TD 98-066

HGQ003 Test Summary Report

J. DiMarco, S. Feher, M.J. Lamm, T. Ogitsu, D. Orris, J.P. Ozelis,
M. Tartaglia, J.C. Tompkins
(FNAL)

January 11, 1999

Contents

List of Figures

List of Tables

Chapter 1

General Overview

1.1 Test Summary Report Outline

This report presents preliminary results of HGQ003 testing at the FNAL Vertical Magnet Test Facility. HGQ003 is the third 70 mm-aperture, short R&D model LHC quadrupole built at FNAL.

The cold testing overview is presented in chapter 1.

Chapter 2 is devoted to quench performance tests. An overview of quench history followed by a quench start locations summary is presented. Relevant test conditions and results are given in summary tables.

Heater studies are presented in Chapter 3. Heater induced quenches were performed at several different excitation currents and heater voltages at 1.9K. The time delay in quench initiation under these various conditions is presented as a function of the normalized current. We determined the minimum voltage of the strip heater firing unit required to quench the magnet at different excitation currents. We also measured the quench integral as a function of the excitation current.

Chapter 4 summarizes strain gauge (SG) runs performed throughout the first test cycle. Included here are summary sheets of all SG runs, and representative plots of coil stress and end force vs. I^2 (where I is the magnet excitation current) to the highest attainable current at each test temperature. Also included are tables summarizing SG readings at 0 A magnet excitation current (warm, before and after cool down), and plots of stress and end forces vs. time (summarizing SG history for the entire first test cycle).

Chapter 5 presents the results of the analysis of quench antenna signal. RRR study is summarized in Chapter 6. Magnetic measurements a re described elswhere.

1.2 Test Overview

HGQ003 was tested according to the runplan attached as an Appendix to this note. The magnet was placed into the VMTF dewar and room temperature magnetic measurements were performed on August 21. HGQ003 was first cooled down on August 27, 1998 and cold testing began on August 28. We were able to achieve only 4.5K for this set of tests since the refrigirator didn't perform very well. The first test cycle ended September 2 with subsequent warm up to room temperature. The second test cycle started on September 8 and ended on September 23, 1998.

1.2.1 Test cycle 1

Initial cooldown was to 4.5K without restriction on the differences between any of the temperature sensors located in the VMTF dewar. The first spontaneous quench of the magnet occurred at 7057A. Four additional quenches were made at the same 20A/sec ramp rate. Since the highest quench current was well below the sort sample limit and the refrigirator had difficulties producing enough liquid helium to keep up with our needs, we continued our test with magnetic measurements. Before the end of the test cycle two additional quenches (20A/sec) were taken. We also tested the EIEO measurement procedure but we didn't take data.

1.2.2 Test Cycle 2

The magnet was cooled down to 4.5K and the first quench of TC 2 occured at 8357 A. One additional quench was made at the same 20 A/sec ramp rate, and the magnet was cooled to 1.9 K. Strain gauge runs were performed, and the first quench at 1.9K occurred at 10019 A. The magnet was quenched 12 additional times. Then we performed three quenches with high ramp rates and after that three quenches were taken with 20A/sec ramp rates. Since the last two quench currents were lower then I_{qmax} we stopped the training.

Next we performed heater studies. We quenched the magnet 8 times using strip heaters and 6 times using spot heaters.

We closed the second test cycle with quench current temperature dependence studies. The magnet was quenched at 4 different temperatures ranging from 1.8K to 4.5K.

During magnet warm up we performed 4 wire resistance measurements to obtain data for RRR studies.

Chapter 2

Quench behavior

This chapter summarizes the quench behavior of the magnet. Instrumentation settings for the HGQ003 test are summarized in Table 2.1 and Table 2.2; a detailed description of the instrumentation and its configuration is presented elsewhere.

Quench data acquisition was performed using the VMTF (pentek) readout system with binary quench data stored on a UNIX workstation. The location of the files are on MTF UNIX cluster:

/vmtf/data/Quench/vmtf.hgq003/

The names of the quench files are summarized in Table 2.4. The data were analyzed using the quenchXmgr utility. HGQ003 had about 96 voltage taps, primarily instrumenting the pole turns and wedges on the four inner and outer coil quadrants and inner/outer coil splice regions.

2.1 Quench history

2.1.1 Test Cycle I

HGQ003 was tested according to the run plan attached as an Appendix to this note. The quench history is summarized in Table 2.3 and in Figure 2.1. Quench testing began at 4.5K at a ramp rate of 20A/s. The first spontaneous quench current was at 7057A, and the six additional quenches at 20A/s successively increased in quench current; the seventh quench reached 9196A. Since the predicted short sample limit of the superconducting cable used in this magnet is 10700kA, the quench current obtained is about 14% below that expected. Difficulties with the refregirator unabled to continue the test, so the magnet was warmed up to room temperature.

2.1.2 Test Cycle II

The magnet underwent thermal cycle to 300K and was cooled back down to 4.5K. The magnet was quenched only twice at this temperature. The 8^{th} spontaneous quench current (first quench of the second test cycle) was at 8357 A. Since, the next quench current was also far below the short sample limit, we cooled the magnet to 1.9K. At 1.9K the magnet was quenched 19 times (quench number 10 - 28) with 20A/sec ramp rates. The 10^{th} (first 1.9K quench of the second test cycle) was at 10019A, which is about 30% below the short sample limit of the cable. Then 3 quenches were taken with 300 A/sec, 150A/sec and 300A/sec ramp rates. Last 3 quenches (20A/sec) at 1.9K increased the quench current to 12180A.

At the end of the second test cycle, 4 additional quenches were taken at temperatures ranging from 1.9K to 4.5K to study quench current dependence on temperature. In these studies, the magnet was ramped to quench at 20A/sec.

2.2 Quench locations

Voltage taps that instrumented HGQ003 allowed for localization of most quenches, however about 10% of the taps were bad and few quench locations were hard to localize. The locations of each spontaneous quenches are summarized in Table 2.3.

Table 2.1: Instrumentation settings - spontaneous quenches

Dump Resistor	Resistance	$60 m\Omega$
	Time Delay	$25 msec$
Power Supply	Time Constant	$0.5 sec$
HFU	Capacitance	$14.4 mF$
	Time Delay	$0 - 20 msec$
	Voltage	$300V@4.3K$
		$350V@1.9K$
Data Logger	Sampling frequency	$7.4 kHz$
	Pre-quench window	50%
Current read back	Hollec	

Table 2.2: QDC settings

AQDC name	Threshold settings	Threshold values
Whole coil	1.0	10 V
Whole coil - Idot	0.09	0.9 V
Bucked Half coils	0.06	0.24 V
SC Leads	0.72	0.03 V
Cu Leads	0.74	0.03 V
Ground	1.26	0.1 V

Table 2.3: Quench history.

Quench num	T [K]	dI/dt [A/s]	I_q [A]	Quench location
1	4.5	19	7057	Q4O16d_Q4O16a Re.end
2	4.5	20	8050	Q4O16b_Q4O16d St.sec
3	4.5	20	8559	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
4	4.5	20	8767	Q1I14c_Q1I14d Re.end
5	4.5	20	8790	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
6	4.5	20	9056	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
7	4.5	20	9195	Q2I14aaQ2I13b
8	4.5	20	8357	Q4O16d_Q4O16a St.sec
9	4.5	20	8643	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
10	1.9	20	10019	Q4O15a_Q4O16b Le.end - 10 mm from 15a
11	1.9	20	10450	Q2I14cQ2I14aa Le.end - 13 cm from 14aa
12	1.9	20	10850	Q4IOrs_Q4I14d Le.end - close to Vtap 14 b
13	1.9	20	10568	Q4I12d_Q4I12c Re.end - 45% from 12c
14	1.9	20	11240	Q2I14aaQ2I13b Le.end - at Vtap 14aa
15	1.9	20	11403	Q4IOrs_Q4I14d Re.end - close to Vtap 14b
16	1.9	20	11572	Q3I11d_Q3I11b St.sec - middle
17	1.9	20	11602	Q1I14c_Q1I14d Re.end - 42% to Vtap 14d
18	1.9	20	11615	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
19	1.9	20	11657	Q1I10b_Q1I11a Le.end - 30% from 10b
20	1.9	20	11740	Q2I14d_Q2I14c Re.end - 41% from 14d
21	1.9	20	11793	Q4I14d_Q4I14c Re.end
22	1.9	20	11838	Q3I13b_Q3I14a Le.end - 30% from 14a
23	1.9	300	11298	Q1I14b_Q4Iors Ramp Splice
24	1.9	150	11756	Q4IOrs_Q4I14d Ramp Splice
25	1.9	300	11593	Q1I14b_Q1IOrs Ramp Splice
26	1.9	20	12012	Q1I14c_Q1I14d Re.end - 3cm from 14d
27	1.9	20	12059	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
28	1.9	20	12180	Q4IOrs_Q4I14d Le.end - close to Vtap 14b
29	2.2	20	11320	Q4I11d_Q4I11c Re.end -
30	3.2	20	11860	Q4I11d_Q4I11c Re.end - middle
31	4.2	20	10915	Q4O16b_Q4O16d St.sec
32	4.5	20	10676	Q2O16d_Q2O16a St.sec

Table 2.4: Quench files

Quench num	File name
1	hgq003.Quench.980829110619.947
2	hgq003.Quench.980829114552.733
3	hgq003.Quench.980829121202.786
4	hgq003.Quench.980829133400.360
5	hgq003.Quench.980829150808.274
6	hgq003.Quench.980901143203.748
7	hgq003.Quench.980901153002.796
8	hgq003.Quench.980908203413.389
9	hgq003.Quench.980908212705.283
10	hgq003.Quench.980909141839.422
11	hgq003.Quench.980909153034.742
12	hgq003.Quench.980909162456.445
13	hgq003.Quench.980909171659.658
14	hgq003.Quench.980909180252.684
15	hgq003.Quench.980909190809.804
16	hgq003.Quench.980909201505.136
17	hgq003.Quench.980910101026.327
18	hgq003.Quench.980910110609.488
19	hgq003.Quench.980910121101.531
20	hgq003.Quench.980911133313.440
21	hgq003.Quench.980911141521.763
22	hgq003.Quench.980911151227.248
23	hgq003.Quench.980911171518.936
24	hgq003.Quench.980911175000.366
25	hgq003.Quench.980914160606.748
26	hgq003.Quench.980914182705.973
27	hgq003.Quench.980914210513.919
28	hgq003.Quench.980914223100.526
29	hgq003.Quench.980918205718.218
30	hgq003.Quench.980918220311.413
31	hgq003.Quench.980918233257.371
32	hgq003.Quench.980919004427.607

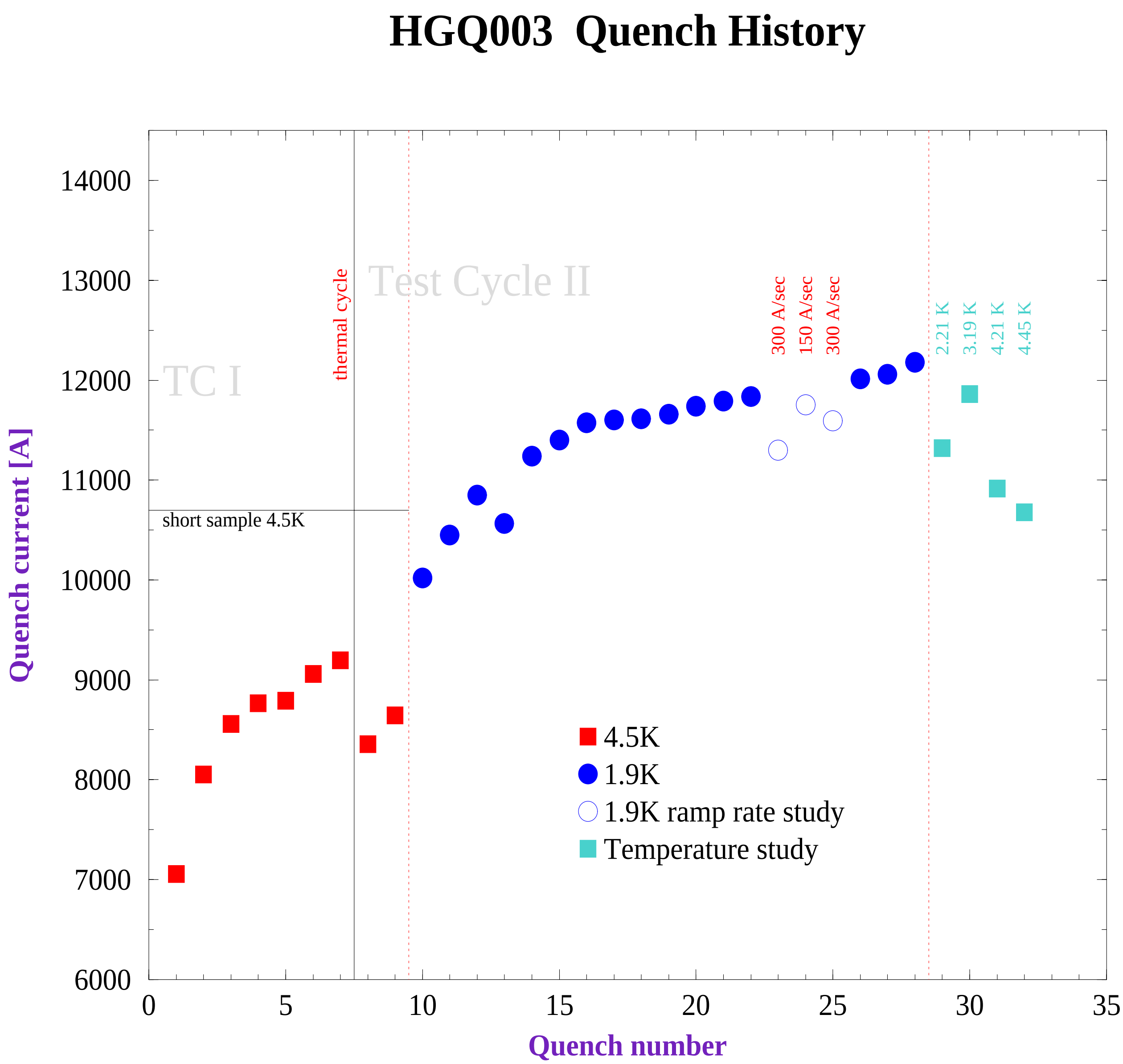

Figure 2.1: Quench history

Chapter 3

Quench protection heater study

This chapter presents the results of the quench protection heater studies.

3.1 Quench protection heaters

The magnet was instrumented with outer and interlayer strip heaters. Spot heaters were also installed in inner and outer coils. The details of these heaters are described elsewhere. The instrumentation settings are summarized in table 3.1. The outer heater was a new LBNL design, called Mac's heater.

3.2 Strip Heater induced quenches

In the strip heater studies, the time delay, t_{fn} (the time from protection heater current initiation to the presence of a detectable quench voltage in the outer coils), and the minimum voltage to initate a quench were measured as a function of various normalized current values (I/I_c). The results for the outer heater are shown in figure 3.1 and figure 3.2. We also gave a summary of results in table 3.2 and table 3.3. In Fig. 3.3 the quench integral is plotted from the onset of voltage growth in the outer coil due to the Mac's strip heaters. Comparing the Mac's heater with other heaters (see test reports of HGQS01 and HGQS02) one can conclude that the new heater is slightly more inefficient as the previous heater design.

3.3 Spot Heater induced quenches

The main purpose of this study was to measure the quench integral vs. the applied current and the quench propagation velocity during spot heater induced quenches. For most of the quenches the dump was not used to extract the energy. It was delayed for 1 sec. The interlayer heater was used to protect the magnet. The applied voltage was 400V. No heater delay was applied.

The Spot heater firing unit voltage was set to 25 V and this value was used for all spot heater studies.

The quench integral (with a starting time at the onset of the spot heater induced resistive voltage) in MIITs ($10^6 A^2 s$) is plotted in Fig. 3.4 as a function of the applied current for quenches induced with the inner spot heaters and protected with the interlayer heaters.

Temperature of inner cable segments vs. the quench integral in MIITs ($10^6 A^2 s$) is plotted in Fig. 3.5 and the results are compared with caculations.

Table 3.1: Instrumentation settings - heater induced quenches

Dump Resistor	Resistance	$60 m\Omega$
	Time Delay	$25 msec$
Power Supply	Time Constant	$0.5 sec$
HFU	Capacitance	$14.4 mF$
	Voltage	$90 - 400V@1.9K$
Data Logger	Sampling frequency	$7.4 kHz$
	Pre-quench window	50%
Current read back	Hollec	

Table 3.2: Heater induced quench files

Quench num	Current [Amps]	temp [K]	Spot heater name & [volt]	Strip heater name & [volt]	File name
1	2840	1.9		Mac 260	hgq003.Quench.980915133041.055
2	2840	1.9		Mac 400	hgq003.Quench.980915134128.060
3	5680	1.9		Mac 400	hgq003.Quench.980915140339.844
4	5680	1.9		Mac 240	hgq003.Quench.980915150518.246
5	9940	1.9		Mac 400	hgq003.Quench.980915151507.424
6	9940	1.9		Mac 160	hgq003.Quench.980916111742.121
7	12000	1.9		Mac 400	hgq003.Quench.980916114618.376
8	12000	1.9		Mac 140	hgq003.Quench.980916135434.765
9	5000	1.9	innerQ4 25	Inter 400	hgq003.Quench.980918110133.733
10	7000	1.9	innerQ4 25	" 400	hgq003.Quench.980918114931.296
11	9000	1.9	innerQ4 25	" 400	hgq003.Quench.980918133817.983
12	10000	1.9	innerQ4 25	" 400	hgq003.Quench.980918151448.738
13	11000	1.9	innerQ4 25	" 400	hgq003.Quench.980918171404.432
14	12000	1.9	innerQ4 25	" 400	hgq003.Quench.980918195135.834

Table 3.3: Heater induced quench measured quantities. (QI = Quench Integral; t = time to start measuring QI; R = resistance, in = inner cable segment, out = outer cable segment; T = temperature)

Quench num	t_{fn} [sec]	QI [MIITs]	QI [MITTs] $t = t_{fn}$	R in [$\mu\Omega$]	T in [K]
1	0.098				
2	0.098		4.72		
3	0.050		10.1		
4	0.043				
5	0.038		13.7		
6	0.033				
7	0.033		13.8		
8	0.029				
9	0.060	13.491		11	68
10	0.060	15.64		21	92
11	0.057	17.31		47	146
12	0.045	17.57		53	157
13	0.032	17.56		56	163
14	0.026	17.58		58	167

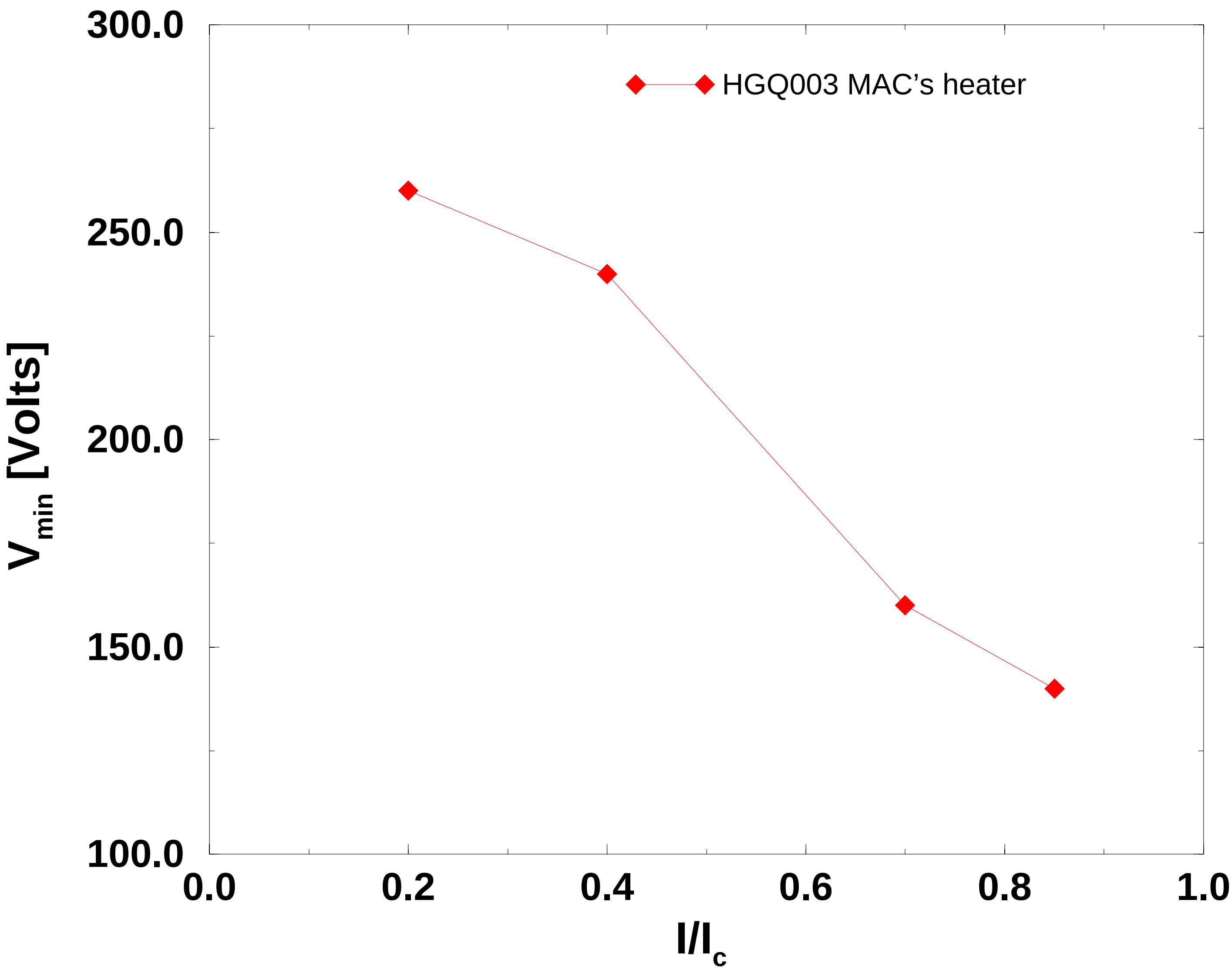

Figure 3.1: Mac's heater induced quenches. Minimum voltage of a heater firing unit is plotted as function of the normalized current.

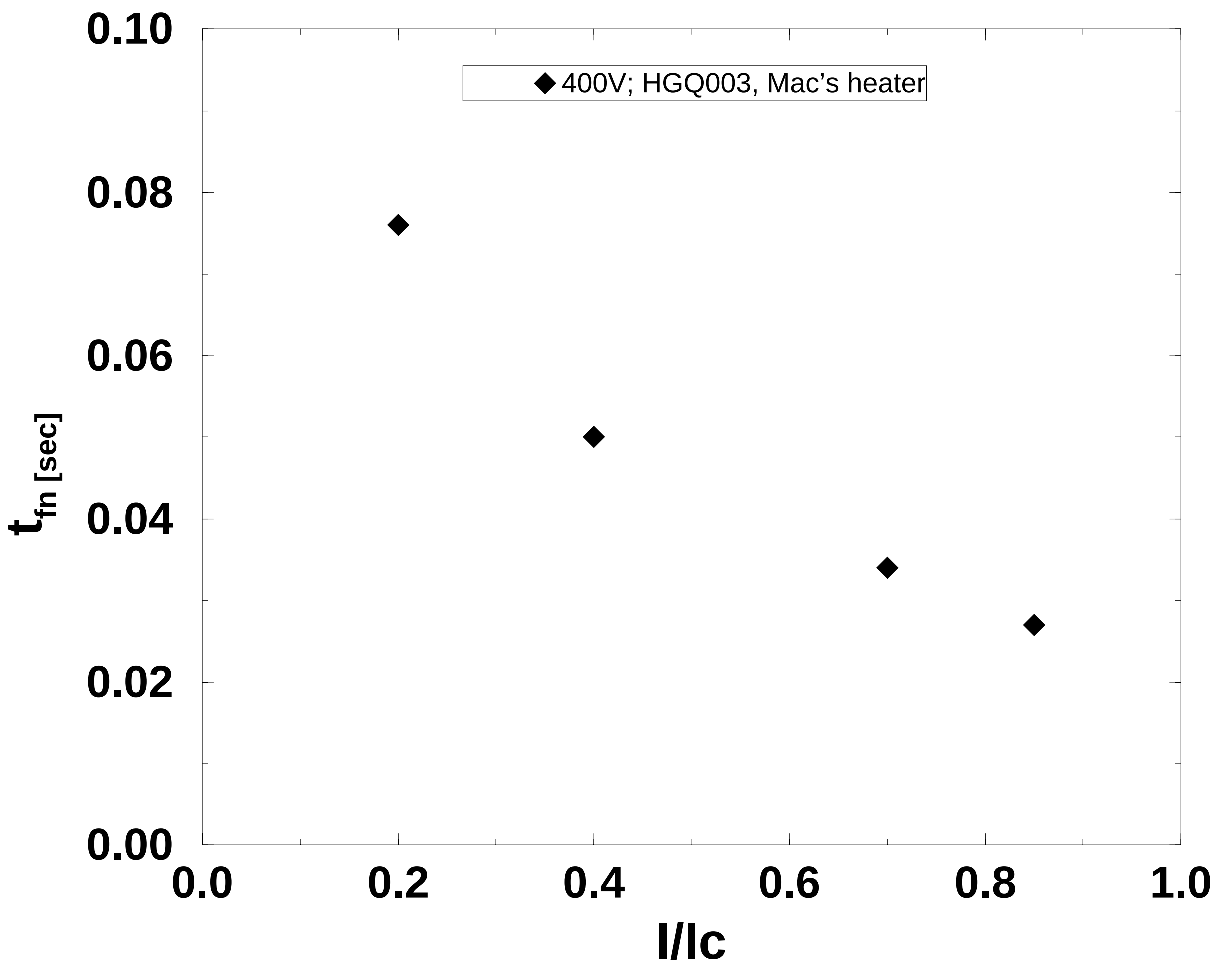

Figure 3.2: Mac's heater induced quenches. t_{fn} is plotted as a function of the normalized current.

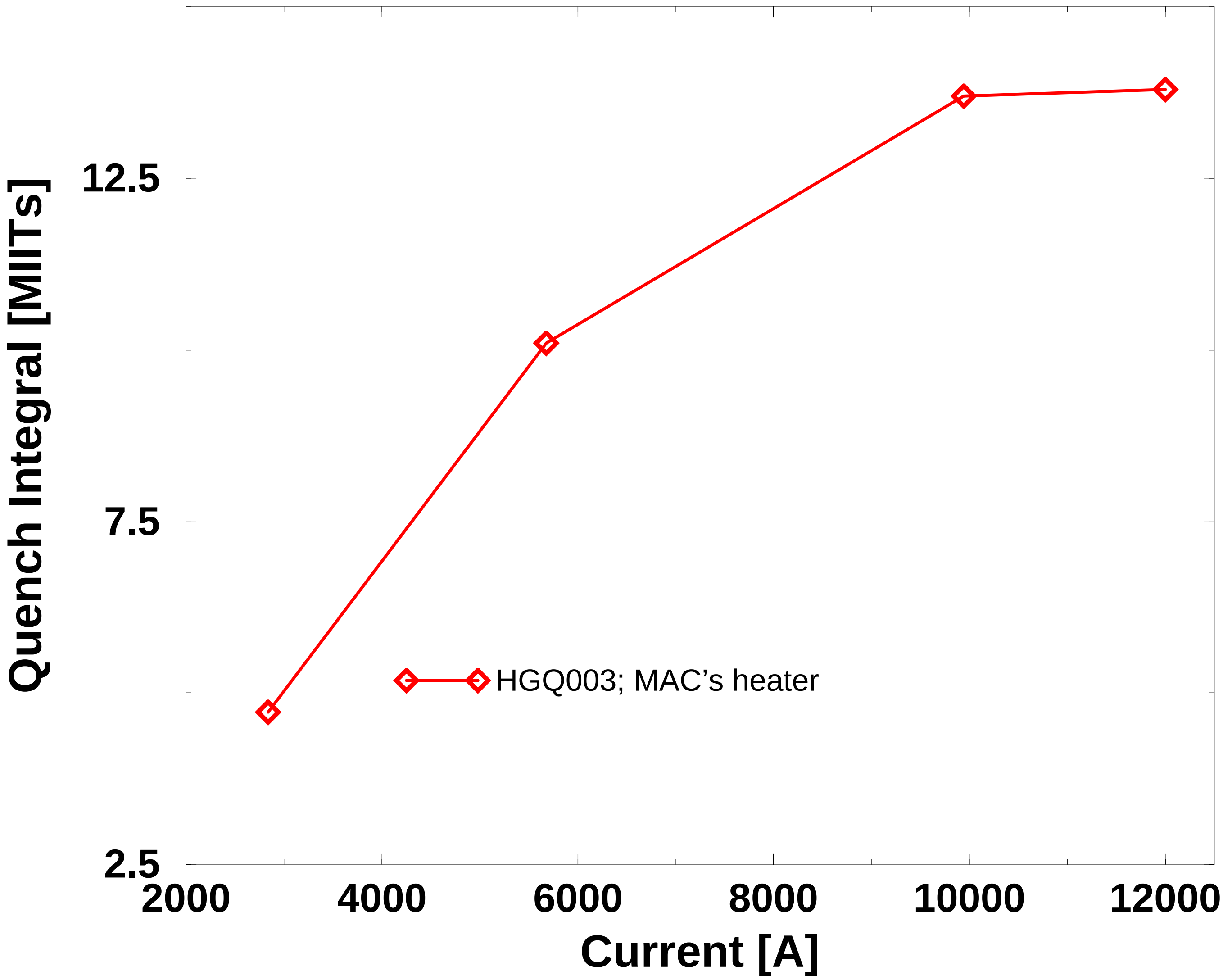

Figure 3.3: Mac's heater induced quenches. Quench integral (from the time the outer cable detected the quench) vs. magnet current is plotted.

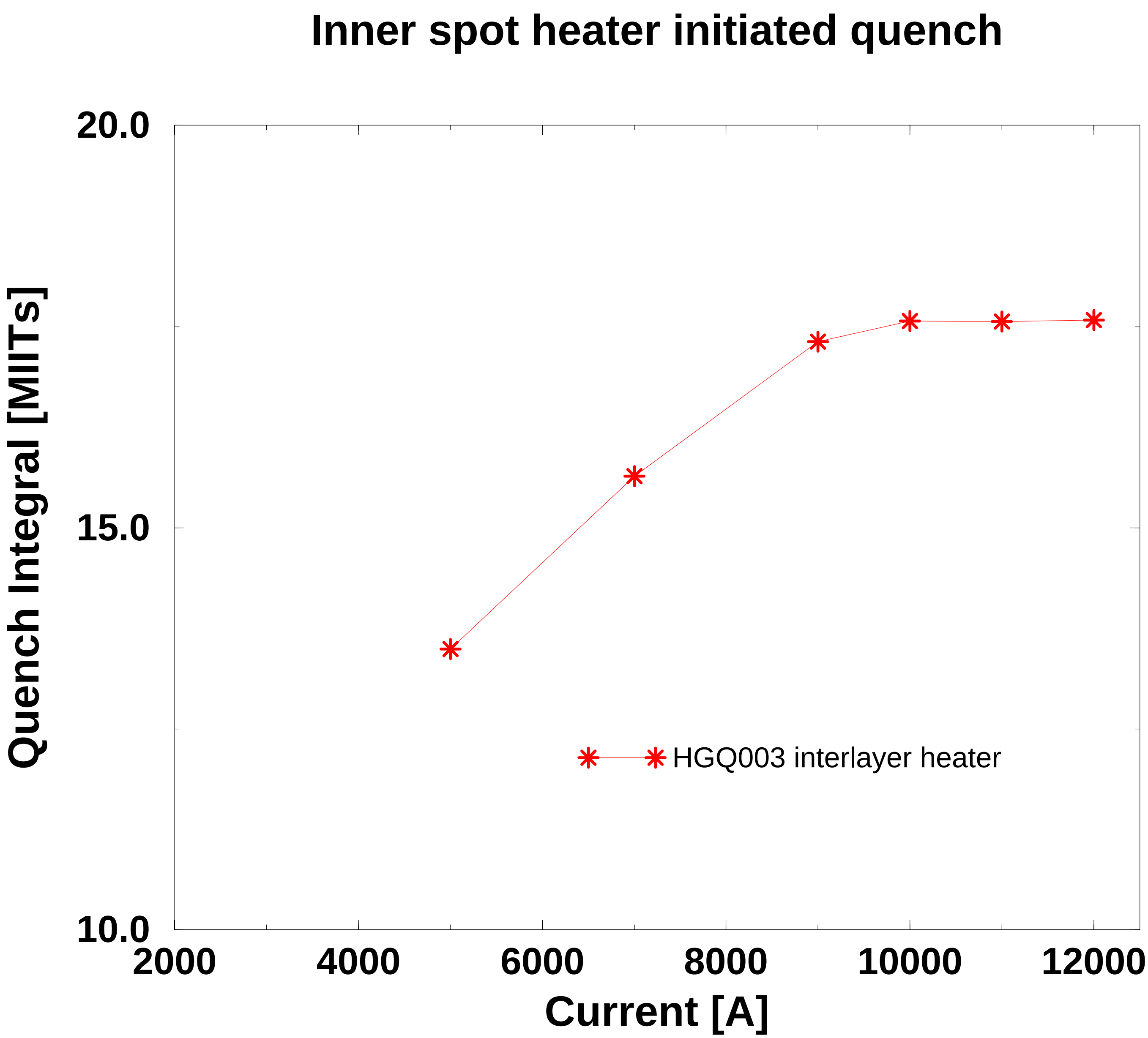

Figure 3.4: Quench integral vs. magnet current for spot heater induced quenches. The magnet is protected with inter layer heaters. The quench integral is calculated from the time of spot heater quench initiation.

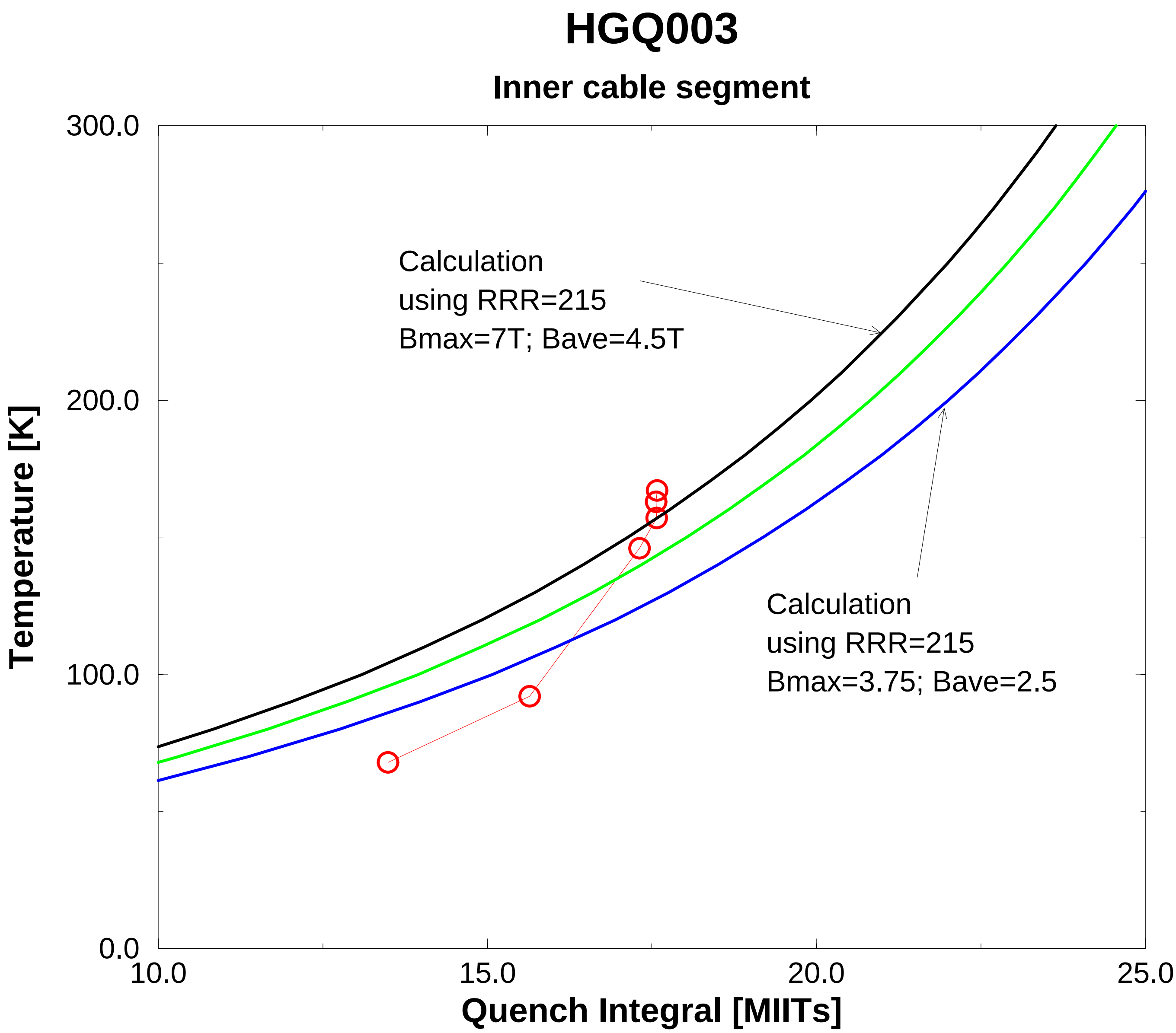

Figure 3.5: Temperature of outer and inner cable segments vs. the quench integral in MIITs ($10^6 A^2 s$) is plotted

Chapter 4

Strain Gauge Results

4.1 Instrumentation Details

Magnet HGQ003 is instrumented with an assortment of strain gauges to measure azimuthal coil stresses, coil end forces, and shell strains. Except for the shell gauges, these strain gauges are calibrated at room temperature and at liquid Helium temperature. All are read out during various phases of the magnet construction process, and during cryogenic testing.

A total of eight beam-type strain gauges are used to measure azimuthal stresses in the straight section of the coils, four mounted at the inner coils, four mounted at the outer coils. Each active strain gauge has a compensating gauge associated with it, whose purpose is to provide an independent measure of the apparent strains induced in the active gauges due to thermal contraction and magneto-resistance effects.

Four capacitance-type strain gauges were also installed in the straight section of the inner and outer coils (2 for each) to measure azimuthal stress. Each of these gauges were installed in such a way that they were in the same collared coil cavity as one of the beam gauges.

A total of eight bullet-type gauges are used to measure the end forces associated with each inner/outer coil pair. Four bullet gauges are mounted at the return-end of the magnet, while four are mounted at the lead end. Each bullet gauge consists of two strain gauges whose readings are subsequently averaged to eliminate strains resulting from bending of the transducer structure. The resultant strain is then used to compute the force on the bullet.

Two compensating gauges are placed at each end of the magnet, whose readings are averaged in order to provide apparent strain data used in eliminating apparent strains from the active gauges.

Skin gauges were mounted in a longitudinal orientation along the weld seam of the shell, essentially equidistant between the return end end-plate and center of the cold mass. Two compensating gauges were used to correct for magneto-resistive effects.

Table 4.1 gives the list of coil azimuthal strain gauges, names, and locations for magnet HGQ03, while Table 4.2 lists the same information for the bullet gauges, and Table 4.3 lists this information for capacitance strain gauges.

4.2 Measurement Schedule

Strain gauge readings are performed several times during the magnet construction and testing cycles. Azimuthal coil stresses, measured with beam-type and capacitance strain gauges, are measured during the collaring and yoking/skinning assembly procedures. After the end plates are installed onto the magnet cold mass, the bullet gauges are then installed and the end loading screws torqued to achieve the desired end loads, while the bullet gauges are monitored. However, for the first test cycle of magnet HGQ003 (which is the subject of this report), no end pre-load was applied to the bullet gauges, in order to investigate the effects of longitudinal coil support on quench performance; therefore, no bullet data is presented in this report.

Once cold mass fabrication has been completed, the magnet is moved to the magnet test facility, and prepared for cryogenic testing. Before, during, and after cryogenic testing all strain gauges are monitored. In particular, strain gauge data is acquired while ramping the magnet before and during quench training at 4.5K and 1.9K. Finally, the strain gauges are read out once the cold mass has been warmed back up to room temperature, so that comparisons with pre-cold test data can be made.

Table 4.1: Beam Gauges

Gauge ID	Type	Coil	Function	Quadrant	End	VMTF Name
LHCI011	Beam	Inner	Active	Quad 1	RE	BmAcQ1IR
LHCI012	Beam	Inner	Active	Quad 3	RE	BmAcQ3IR
LHCI018	Beam	Inner	Active	Quad 2	LE	BmAcQ2IL
LHCI019	Beam	Inner	Active	Quad 4	LE	BmAcQ4IL
LHCTC15	Beam	Inner	Comp	Quad 1	RE	BmCoQ1IR
LHCTC6	Beam	Inner	Comp	Quad 3	RE	BmCoQ3IR
LHCTC9	Beam	Inner	Comp	Quad 2	LE	BmCoQ2IL
LHCTC46	Beam	Inner	Comp	Quad 4	LE	BmCoQ4IL
LHCO009	Beam	Outer	Active	Quad 2	RE	BmAcQ2OR
LHCO010	Beam	Outer	Active	Quad 4	RE	BmAcQ4OR
LHCO013	Beam	Outer	Active	Quad 1	LE	BmAcQ1OL
LHCO016	Beam	Outer	Active	Quad 3	LE	BmAcQ3OL
LHCTC17	Beam	Outer	Comp	Quad 2	RE	BmCoQ2OR
LHCTC8	Beam	Outer	Comp	Quad 4	RE	BmCoQ4OR
LHCTC47	Beam	Outer	Comp	Quad 1	LE	BmCoQ1OL
LHCTC48	Beam	Outer	Comp	Quad 3	LE	BmCoQ3OL

4.3 Results

The azimuthal coil stresses as measured by beam gauges are summarized in Table 4.4, which shows the coil stresses (measured in psi) during various fabrication and operational conditions. Also presented is the average coil stress change during cooldown from 300K to 4.5K (or 1.9K) and also the dynamic change in coil stress as a function of the square of the excitation current. Figure 4.1 shows the azimuthal coil stress history of the cold mass during fabrication, through yoking/skinning in ICB, and at various cryogenic conditions.

In Figures 4.2 and 4.3 we show the results of strain gauge and skin gauge measurements as a function of I^2 for a quench run to 12092A at 1.9K. Note that the azimuthal coil stresses remain non-zero for all values of excitation current. There is no evidence of coil unloading at even the highest

Table 4.2: Bullet Gauges

Production Gauge Nam	VMTF Gauge Nam	Gauge Type	Gauge Location	Remarks
BL17A/B	BuQ1R	Bullet, active	Quad 1, RE	
BL18A/B	BuQ4R	Bullet, active	Quad 4, RE	
BL19A/B	BuQ2R	Bullet, active	Quad 2, RE	
BL20A/B	BuQ3R	Bullet, active	Quad 3, RE	
BL21A/B	BuQ1L	Bullet, active	Quad 1, LE	
BL22A/B	BuQ2L	Bullet, active	Quad 2, LE	
BL23A/B	BuQ3L	Bullet, active	Quad 3, LE	
BL24A/B	BuQ4L	Bullet, active	Quad 4, LE	
BT31	BuCoR_1	Bullet, comp.	RE	Comp. for RE bullets
BT32	BuCoR_2	Bullet, comp.	RE	“
BT33	BuCoL_1	Bullet, comp.	LE	Comp. for LE bullets
BT34	BuCoL_2	Bullet, comp.	LE	”

current level reached. Furthermore, extrapolation indicates that the lowest pre-loaded coil would only reach zero azimuthal stress at currents above 15 kA, well above the designed operating current and short sample limit.

The skin gauges indicated marginal levels of skin stress as a function of I^2 (Fig. 4.3), primarily at the center of the cold mass. At 12092A, we find about $12 - 15\mu\varepsilon$ at the location of the gauges at and within 30cm of the magnet center, while at the return end and within 50 cm of it, the measured strains were negligible.

The plots shown in Figures 4.2 and 4.3 are typical of all of the quench runs at 4.5K and 1.9K. No anomalous behavior was observed during cryogenic testing. Additional data/plots can be found at http://mdtf20.fnal.gov/ ozelis/HGQ03_SG/hgq03_sum.html. The dynamic mechanical behavior of magnet HGQ003 is summarized in Table 4.5. This behavior is very similar to that of previous HGQ model magnets

Table 4.3: Capacitance Gauges

Gauge ID	Coil	Function	Quadrant	End	VMTF Name
HQCGI44	Outer	Active	Quad 4	LE	CgAcQ4OL
HQCGI41	Inner	Active	Quad 2	RE	CgAcQ2IR
HQCGI42	Inner	Active	Quad 4	RE	CgAcQ4IR
HQCGI43	Outer	Active	Quad 2	LE	CgAcQ2OL

Table 4.4: Coil Stresses (in psi)

Sensor Name	Stress(comp.) PSI (IB3)	Stress(comp.) PSI (VMTF)	Stress(comp.) PSI (4.45K)	Stress(comp.) VMTF 4.5K	Stress(comp.) VMTF 4.5K	Stress(comp.) VMTF 1.9K	Stress(comp.) VMTF 1.9K
LHCI011 (BmAcQ1IR)	22276	22562	25167	24910	21879	24850	17734
LHCI012 (BmAcQ3IR)	33874	33784	30416	30314	28671	30211	25625
LHCI018 (BmAcQ2IL)	30153	31307	26450	26190	23756	26241	20048
LHCI019 (BmAcQ4IL)	22228	21908	20617	20304	16884	20726	12890
Average	27133	27390	25663	25430	22798	25507	19074
				-1961	3.85E-05	-1883	4.4E-05
				Cooldown $\Delta\sigma$	$\Delta\sigma/\Delta I^2$	Cooldown $\Delta\sigma$	$\Delta\sigma/\Delta I^2$
LHCO009 (BmAcQ2OR)	20317	20415	18849	18888	17553	19354	16540
LHCO010 (BmAcQ4O)	15199	15443	22438	22401	20562	21926	17964
LHCO013 (BmAcQ1OL)	10919	10930	9783	9824	8688	10166	7680
LHCO016 (BmAcQ3OL)	9670	9688	8232	8237	7340	8818	6827
Average	14026	14119	14826	14838	13536	15066	12253
	Date		8/31/98	9/7/98	9/7/98	9/13/98	9/13/98
	Condition		I=0	I=0	I=8270	I=0	I=12092
				-1961	3.85E-05	-1883	4.4E-05
				Cooldown $\Delta\sigma$	$\Delta\sigma/\Delta I^2$	Cooldown $\Delta\sigma$	$\Delta\sigma/\Delta I^2$

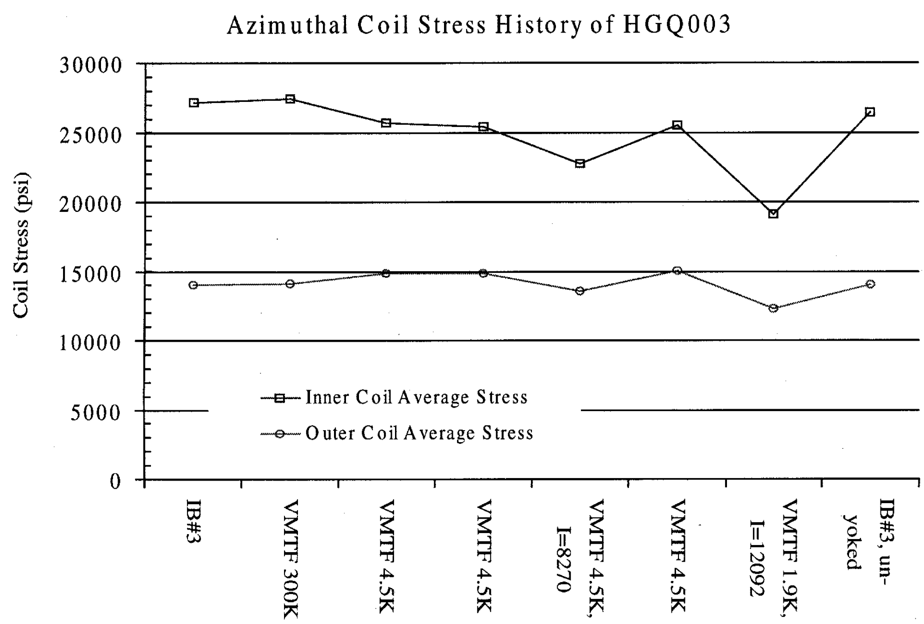

Figure 4.1: Summary of azmiuthal coil stress as measured by beam gauges.

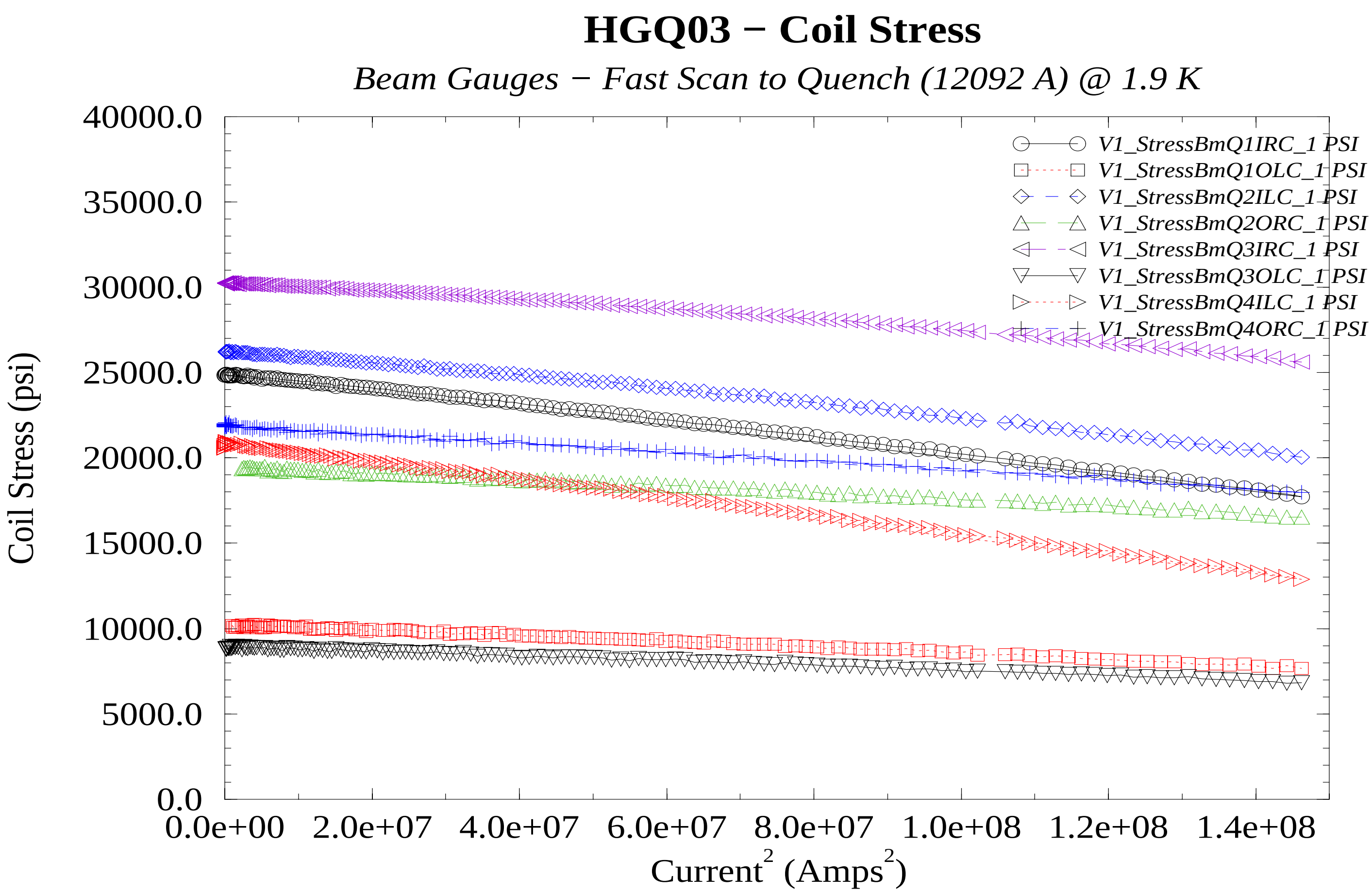

Figure 4.2: Azimuthal coil stress measured by beam gauges for a run to quench (12092A) at 1.9K.

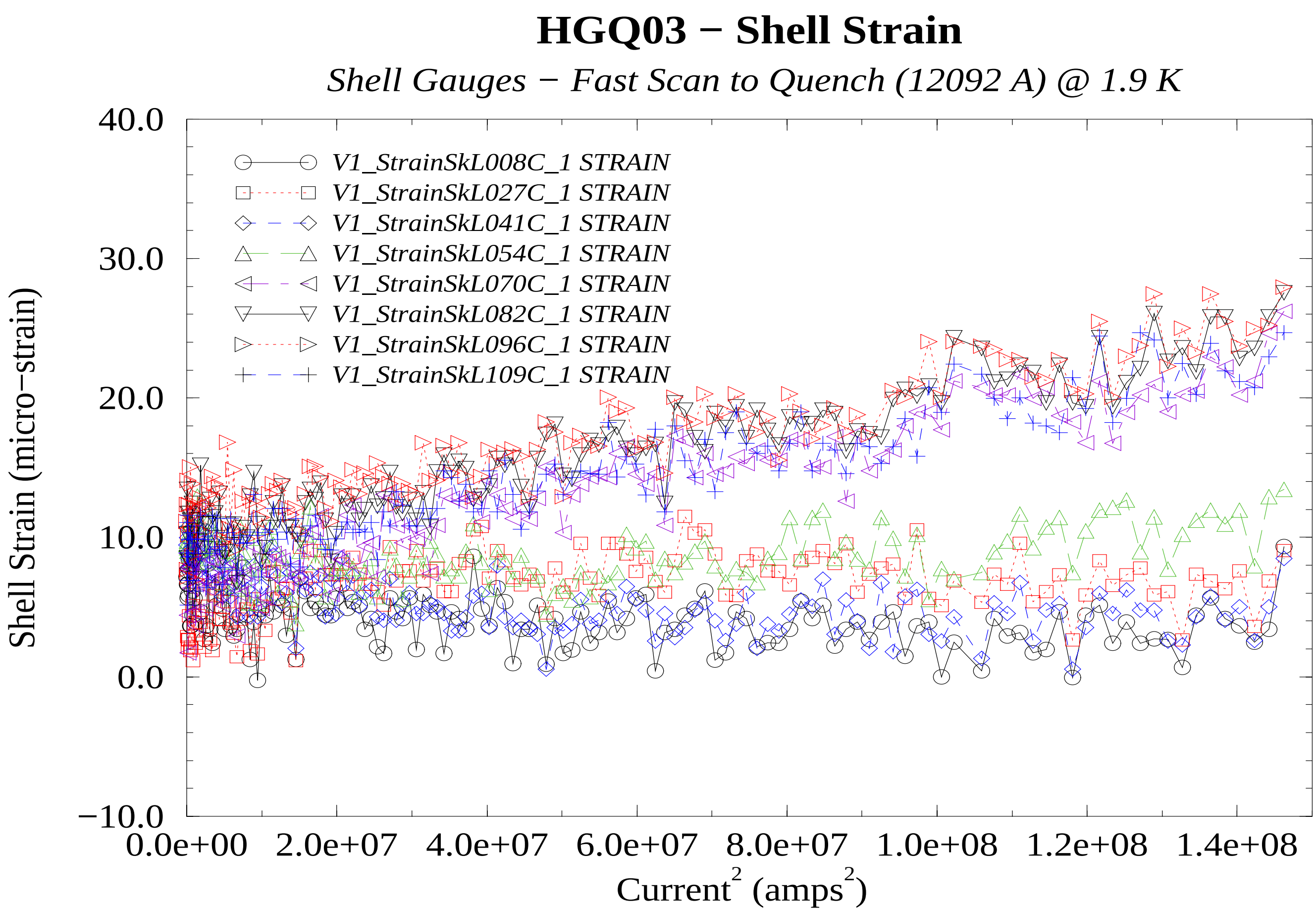

Figure 4.3: Longitudinal shell strains measured during a run to quench (12092 A) at 1.9K.

Table 4.5: Cryogenic Test Results

	measured	design
Average Inner Coil Stress 300K	$27115psi$ ($187MPa$)	$12000psi$ ($81MPa$)
Average Outer Coil Stress 300K	$13920psi$ ($96MPa$)	$12000psi$ ($81MPa$)
Average Inner Coil Cool-Down Loss	$-1960psi$ ($-14MPa$)	$-600psi$ ($-4MPa$)
Average Outer Coil Cool-Down Loss	$+720psi$ ($+5MPa$)	$-1450psi$ ($-10MPa$)
Average Inner Coil Lorentz Loss	$4.13x10^{-5}psi/A^2$ ($2.9x10^{-7}MPa/A^2$)	$4.4x10^{-5}psi/A^2$ ($3.0x10^{-7}MPa/A^2$)
Average Outer Coil Lorentz Loss	$1.91x10^{-5}psi/A^2$ ($1.3x10^{-7}MPa/A^2$)	$2.9x10^{-5}psi/A^2$ ($2.0x10^{-7}MPa/A^2$)

Chapter 5

Quench antenna

A quench antenna was used for some of the training quenches on hgq003. Quench antenna is a series of 3 identical coil arrays, each of which contain four independent pickup coils: each array is sensitive to normal sextupole, skew sextupole, normal octupole, and skew octupole field. The signals of these four coils allow us to obtain the radial and azimuthal quench location of a quench front, while the series of coil arrays, axially aligned in the magnet bore, give the axial location. The coil arrays were named antenna-1, antenna-2, and antenna-3.The length of each coil is 350 mm and they are aligned with interval of 465 mm. Antenna-2 is at the center of the magnet, antenna-1 is at the lead end and antenna-3 is at the return end. The radius of the coils is approximately 22 mm.

Figure 5.1 shows typical signals of a coil array: the signals are those of antenna-2 and taken during the 16-th quench, where the quench started in the middle of straight section Q3I11d-I11b. At t = -0.016 sec, signals start to change simultaneously due to a local field change created by a quench front which causes current movement. For this quench, the time when signals start corresponds to the time the quench started, indicating the quench origin is within the extent of this coil. This agrees with what we derived from voltage tap signals. Radial and Azimuthal localization is performed using the equation 5.1, 5.2, 5.3, and 5.4,

$$V_6 n = -NL\frac{3\mu_0 I v}{\pi}\sum_{n=2\,8\ldots} r_c^{n+1}\left(\frac{1}{r_s^{n+2}}cos\left(-\left(n+2\right)\alpha+\beta\right)-\frac{r_s^n}{R^{2n+2}}cos\left(-\left(n\alpha-\beta\right)\right)\right) \quad (5.1)$$

$$V_6s = -NL\frac{3\mu_0 Iv}{\pi}\sum_{n=2\,8\,\ldots} r_c^{n+1}\left(\frac{1}{r_s^{n+2}}sin\left(-\left(n+2\right)\alpha+\beta\right)-\frac{r_s^n}{R^{2n+2}}sin\left(-\left(n\alpha-\beta\right)\right)\right) \tag{5.2}$$

$$V_8n = -NL\frac{4\mu_0 Iv}{\pi}\sum_{n=3\,11\,\ldots} r_c^{n+1}\left(\frac{1}{r_s^{n+2}}cos\left(-\left(n+2\right)\alpha+\beta\right)-\frac{r_s^n}{R^{2n+2}}cos\left(-\left(n\alpha-\beta\right)\right)\right) \tag{5.3}$$

$$V_8s = -NL\frac{4\mu_0 Iv}{\pi}\sum_{n=3\,11\,\ldots} r_c^{n+1}\left(\frac{1}{r_s^{n+2}}sin\left(-\left(n+2\right)\alpha+\beta\right)-\frac{r_s^n}{R^{2n+2}}sin\left(-\left(n\alpha-\beta\right)\right)\right) \tag{5.4}$$

where V_6n, V_6s, V_8n, and V_8s are the voltages of normal sextupole, skew sextupole, normal octupole, and skew octupole antenna coil, N is the number of turns, L is the length, r_c is the radius of the antenna coils, R is the radius of the yoke, r_s is the radial position of the moving current, α is the angular position, β is the direction, I is the current, v is the velocity. The time between -0.015 and -0.008 sec, which corresponds to the first pulse duration, is taken as an analysis range and each signal is integrated for this time range and then applied to the equations. The analysis result shows that the quench origin is at the Q3I11d-I11d which agrees with the voltage tap result. Table 5.1 summarizes quench localization of all the quenches performed with quench antenna installed. The table summarizes the radial position r_s and azimuthal position α of the quenches as well as the current movement direction β and the strength Iv. The axial location is indicated by the antenna whose signal started first.

Quench localization using the quench antenna agrees very well with that of voltage taps for most of the quenches that occurred in the inner layer. The localization for outer coil quenches, however, did not agree very well. They agree in terms of axial location and quadrant, but not for radial position, nor turn. This may be due to the fact that the signal caused by outer coil quench is mostly shielded by the inner coil and that the signal actually detected by the antenna is not that created by the original quench but that caused by the induced quench in the corresponding inner coil.

Table 5.1: Quench files

Quench Number	File Name	Analysis Range sec		Axial Position	Radial Position m	Azimuthal Position rad	Moment Direction rad	Moment Strength Am
1	hgq003.Quench.980829110619.947	-0.014	-0.007	Ant-3	0.027	-2.020	-3.170	0.00135
2	hgq003.Quench.980829114552.733	-0.011	-0.006	Ant-1	0.029	-1.859	-1.692	0.00301
3	hgq003.Quench.980829121202.786	-0.024	-0.012	Ant-1	0.036	-2.458	-5.832	0.1744
8	hgq003.Quench.980908203413.389	-0.008	-0.004	Ant-3	0.034	-1.672	-0.185	0.0039
9	hgq003.Quench.980908212705.283	-0.023	-0.010	Ant-1	0.036	-2.432	-5.960	0.1710
10	hgq003.Quench.980909141839.422	-0.008	-0.003	Ant-1	0.032	-1.931	-2.025	0.0038
11	hgq003.Quench.980909153034.742	-0.024	-0.019	Ant-1	0.048	0.980	2.455	0.0190
12	hgq003.Quench.980909162456.445	-0.015	-0.006	Ant-1	0.036	-2.471	-5.803	0.2135
13	hgq003.Quench.980909171659.658	-0.008	-0.001	Ant-3	0.046	4.272	0.307	0.0776
14	hgq003.Quench.980909180252.684	-0.018	-0.014	Ant-1	0.035	-5.301	-4.763	0.0106
15	hgq003.Quench.980909190809.804	-0.015	-0.005	Ant-1	0.035	-2.456	0.185	0.1846
16	hgq003.Quench.980909201505.136	-0.016	-0.012	Ant-2	0.044	-1.093	-3.004	0.0270
17	hgq003.Quench.980910101026.327	-0.018	-0.008	Ant-3	0.053	-3.845	-4.880	0.0751
18	hgq003.Quench.980910110609.488	-0.014	-0.005	Ant-1	0.035	-2.442	-5.803	0.1667
19	hgq003.Quench.980910121101.531	-0.014	-0.005	Ant-1	0.036	1.809	0.318	0.0091
20	hgq003.Quench.980911133313.440	-0.014	-0.009	Ant-3	0.052	0.556	2.247	0.0327
21	hgq003.Quench.980911141521.763	-0.015	-0.011	Ant-1	0.037	-5.260	-4.506	0.0115
22	hgq003.Quench.980911151227.248	-0.007	0.0	Ant-1	0.045	-0.484	-2.520	0.0478
23	hgq003.Quench.980911171518.936	-0.010	-0.004	Ant-1	0.041	-4.063	-4.934	0.0819
24	hgq003.Quench.980911175000.366	-0.008	0.0	Ant-1	0.035	-2.430	-5.719	0.8565

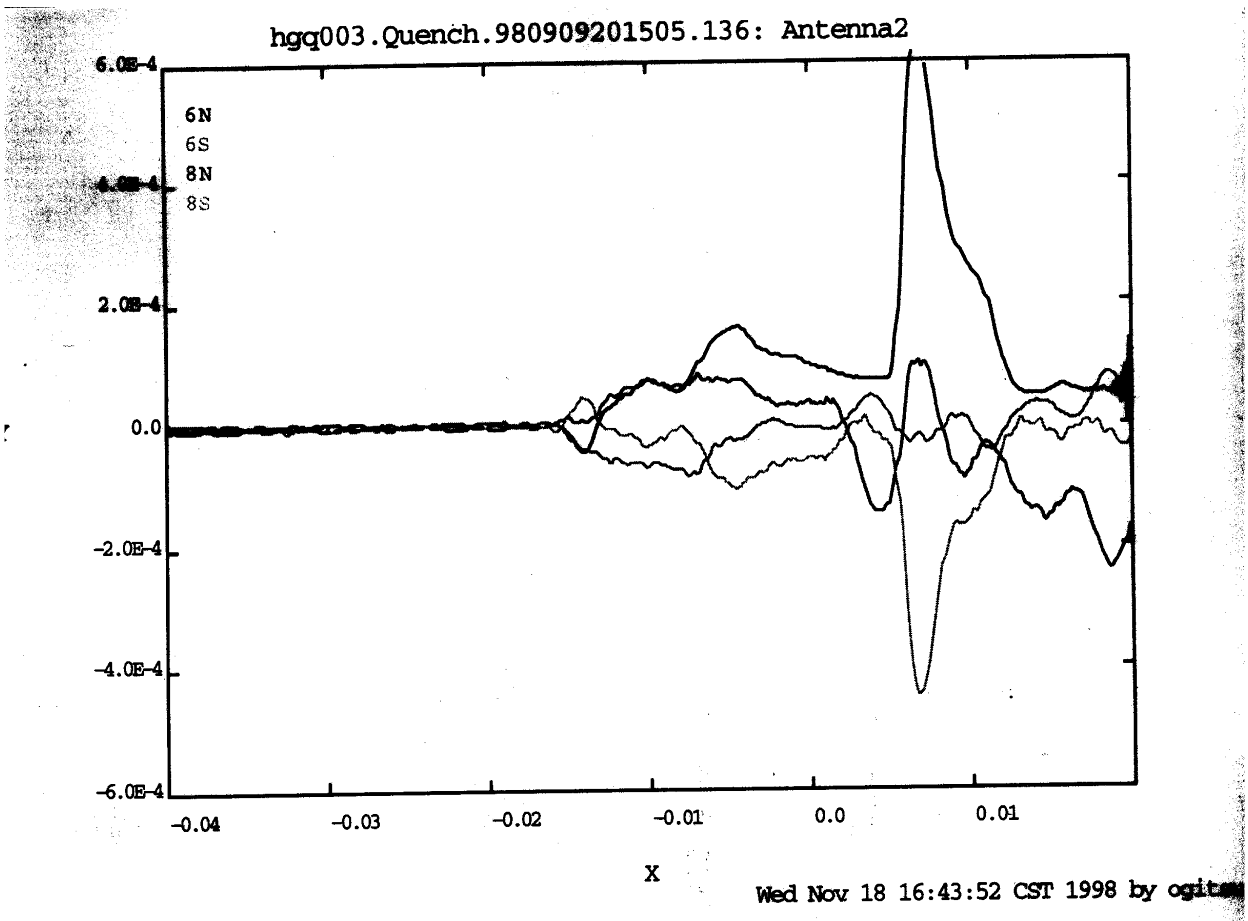

Figure 5.1: Quench antenna signals; quench number 16 antenna-2

Chapter 6

RRR study

This chapter summarizes the residual resistance ratio (RRR) measurements. RRR is determined by measuring the coil resistance and temperature during magnet warm up.

Measurements of magnet resistance were made using a 4-wire technique at a current of 10A. Current was supplied by a Hewlett Packard Power Supply and voltages measured through the magnet voltage taps . Both voltage and current measurements were made using HP3458A DMMs. For measurement of temperature we used Carbon-Glass sensors in the vicinity of the magnet. Two sensors were used, one of them closer to the top of the magnet and the other closer to the bottom. Note that these sensors were in fact reading the gas temperature and therefore one would expect the actual magnet temperature to be somewhat different. We also used a Carbon-Glass sensor which was attached to the collar lamination - it was in thermal contact with it.

Figures 6.1 and 6.2 compare the resistances of the eighth coils, measured while the magnet was gradually warming up, against the calculated room temperature resistances. For these plots, the average temperature of the top and bottom carbon glass sensors was used. We observed that the parameterization curve constrained by the resistance values measured at the lower temperatures does not agree well with the data measured at the higher temperatures. However, the magnet resistance around 10 K is not temperature dependent and therefore the error in RRR introduced by basing measurements on these points is not significant ($< 10\%$).

Figures 6.3 and 6.4 also compare the resistances of the eighth coils, measured while the magnet was gradually warming up, against the calculated room temperature resistances, but for the carbon glass sensor used for these plots was the sesor which was attached directly to the collar. The agreement with the parametrization is reasonable.

Note that the RRR value for the inner coil (~ 225) is significantly larger than that of the outer coil (~ 95). This is not necessarily a surprise since the inner and outer cable strands are made from completely different billets. It also interesting to point out that HGQ003 cable RRR value was about 1.6 times higher than that of HGQS01 cable, but it was about the same value as the HGQS02 cable RRR value . This might be due to a different coil curing process.

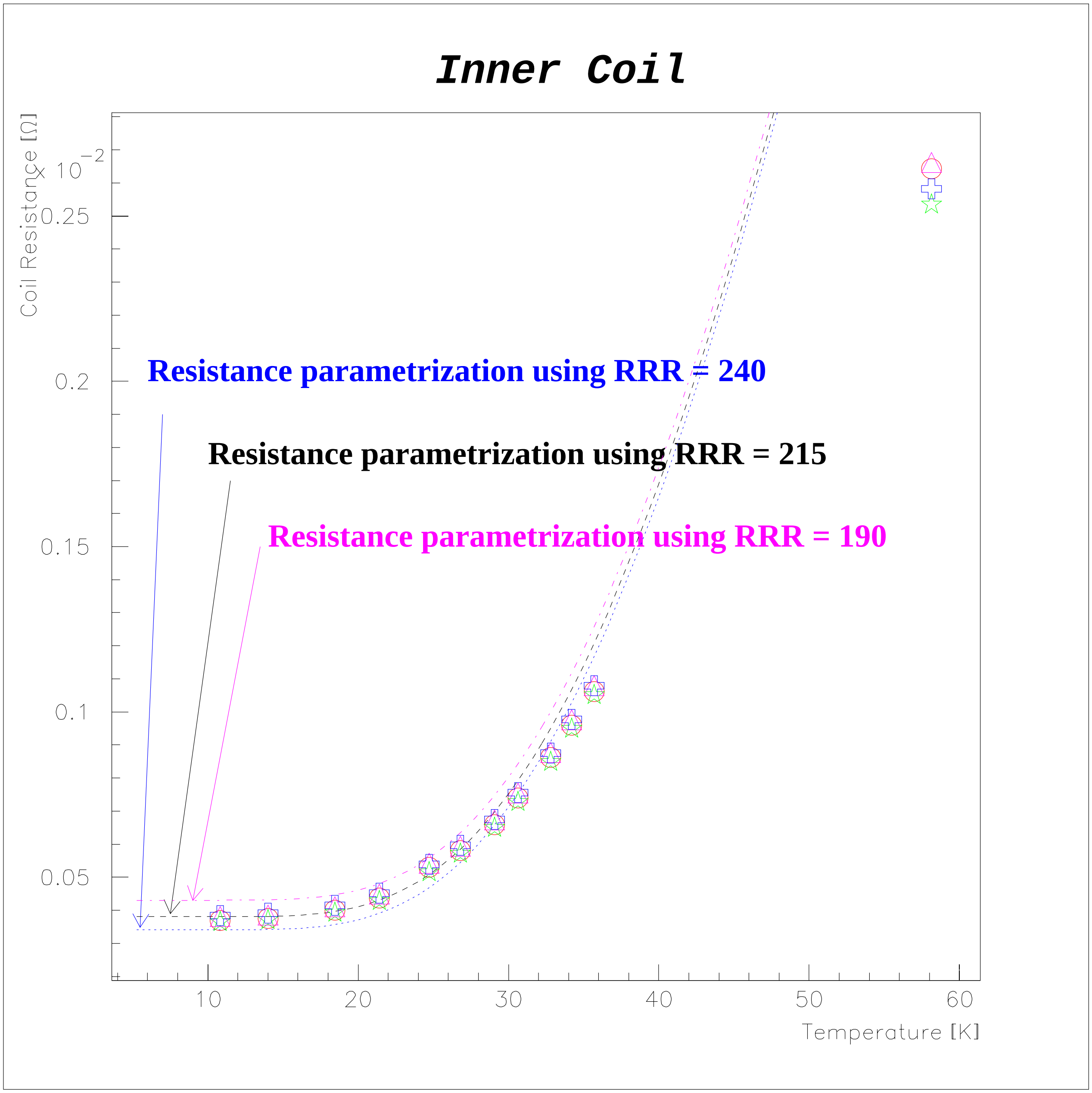

Figure 6.1: Inner coil resistance temperature dependence comparison with parametrization.

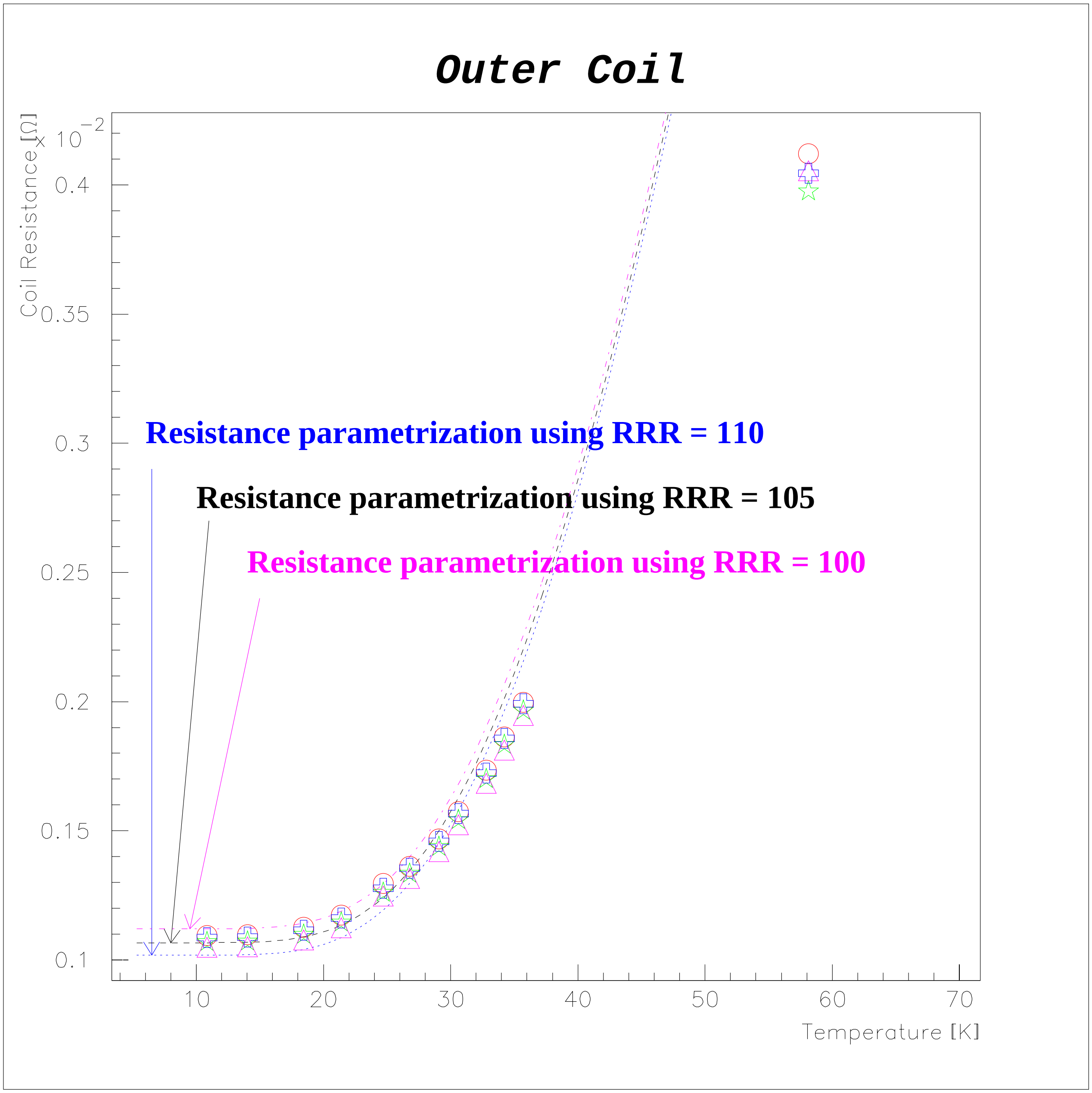

Figure 6.2: Outer coil resistance temperature dependence comparison with parametrization.

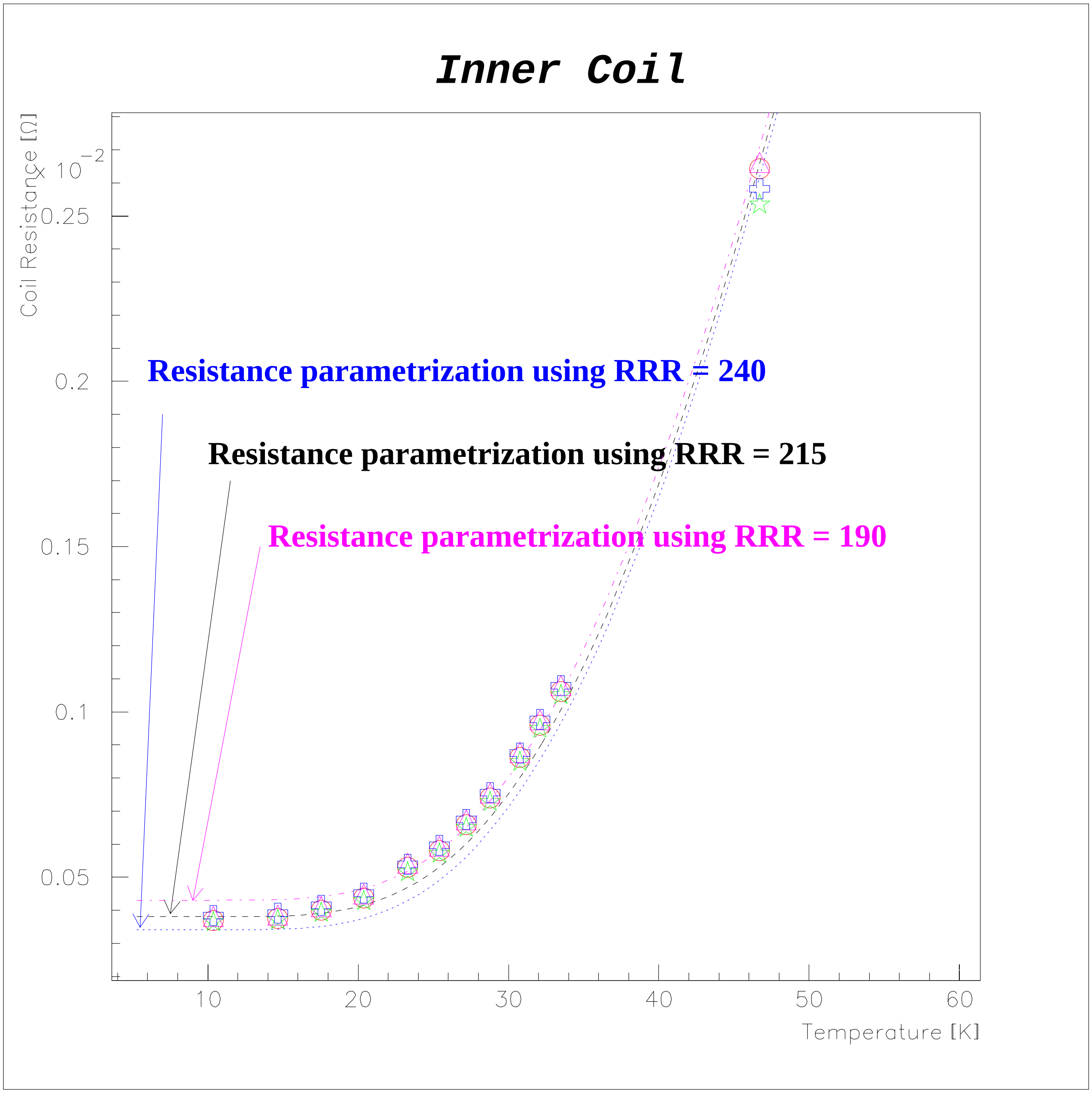

Figure 6.3: Inner coil resistance temperature dependence comparison with parametrization.

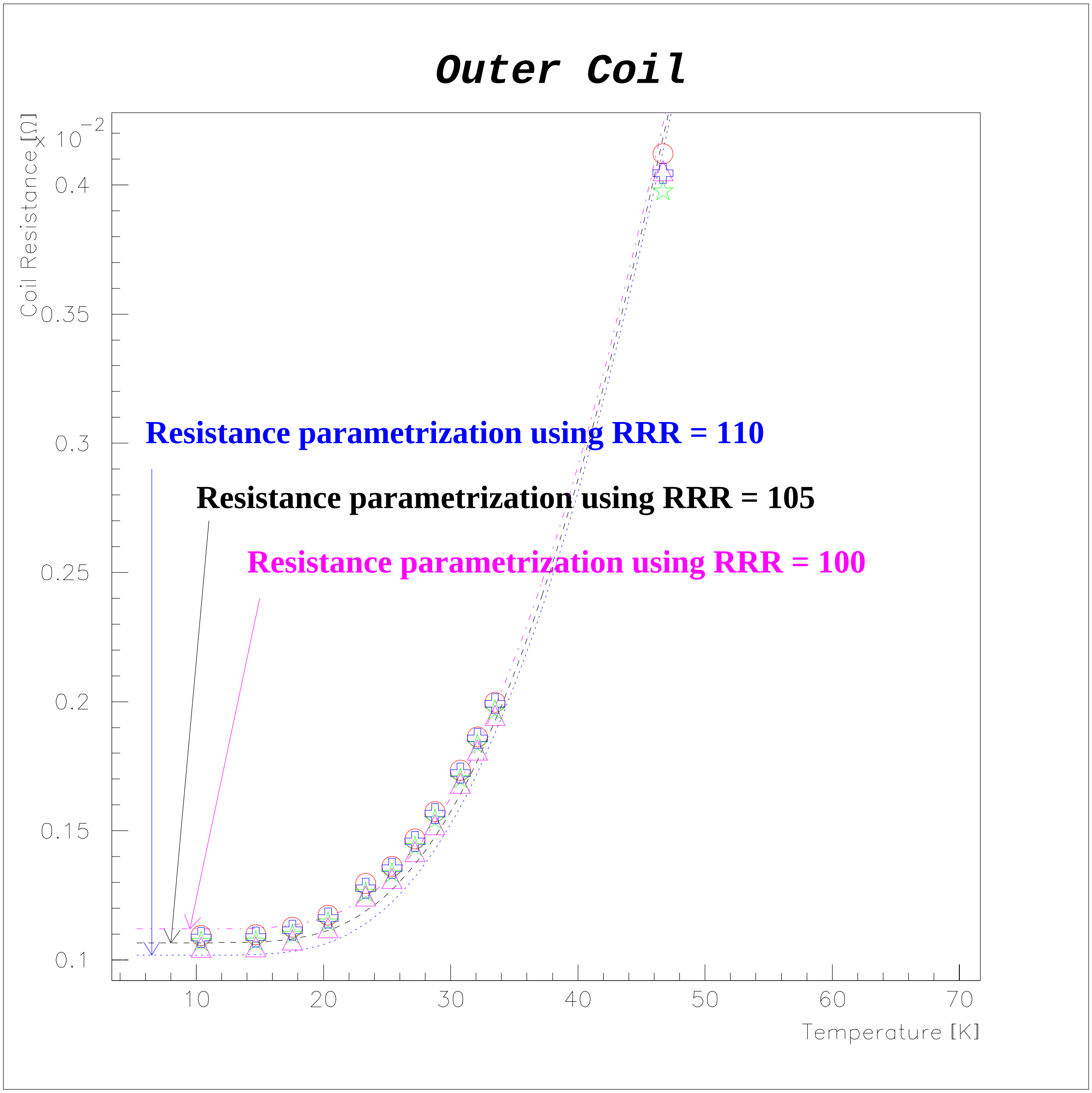

Figure 6.4: Outer coil resistance temperature dependence comparison with parametrization.

Appendix A

HGQ003 TEST PLAN

A.1 Outline

Test Cycle I

- Magnetic measurements
- Room Temperature Pretest and Cool down
  RRR
- At 4.5K Operation
  Pre-Current excitation Checkout
  2500 amp Heater test
  Strain gauge runs
  Quench Plateau (max. 5 quenches)
  Ramp Rate Studies
- At 1.9K Operation
  Pre-current excitation Checkout
  3000 amp Heater tests
  Strain gauge runs
  Quench Plateau

Ramp rate studies

Magnetic measurements

Heater studies (outer, interlayer, spot heater)

Quench Current vs. temperature

RRR

Test Cycle II

- At 1.9 K Operation

  Pre-current excitation Checkout

  Quench Plateau

  Magnetic measurements Energy loss measurement

A.2 Test cycle I

A.2.1 Magnetic measurements

1. Without Yoke
2. With Yoke
3. In the dewar (optional)
   (a) Locate magnetic center by scanning ends
   (b) Apply ± 10 A. Take measurements at 8 different z locations: 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.0 m. At each z step make 25 rotations. Take these readings with "amplifiers in".
4. Remove the measurement rig and install the quench antenna

A.2.2 Room Temperature Pretest/Cooldown

1. Follow present procedures for strain gauge, voltage taps, thermometer, and heater validation. Procedures include:
   (a) Hi pot the magnet in gaseous He environment. Maximum volts should not exceed V_{max} value (to be determined).

(b) 4 wire measurement of all strain gages

(c) 5 amps across magnet, measure voltage across taps Measure magnet resistance and compare it to the value measured at IB3. Verify that there are no shorts in the magnet

(d) 4 wire heater resistance, system resistance for all four heaters.

2. Record at least 10 strain gage readings at room temperature, check values with post assembly readings.

3. Set strain gage and thermometer readings to 10 minute intervals

4. Place 5 amps through magnet, measure voltage across magnet (each eigth coils separately).

5. Cool down to 80K, then change strain gage and thermometer readings to 1 minute intervals. Cool to 4.5 K , 1.1 ATM with unrestricted cooldown following VMTF cool-down procedure and take volage readings for RRR studies (make sure to get data around ~10 K). Take Strain gauge runs as well. Verify that no shorts appeared during cooldown.

A.2.3 At 4.5 K Operation

1. Cold electrical tests prior to magnet testing

   (a) Check magnet resistance to ground

   (b) Hi pot (1.1 ATM helium). Maximum volts should not exceed V_{max} value (to be determined).

   (c) Make sure that strain gauge readings are recorded

   (d) Protect magnet with a 60 mΩ dump resistor. $I_{max} * R_{dump} \leq 1000V$

   (e) Heater Pretests

      i. Configure QLM to fire heater with 1 sec dump firing delay

      ii. Check outer and inter-layer heater and heater system resistance using 4 wire techniques. System capacitance should be set to approximately 14.4 mF.

iii. Verify that inter-layer and outer heaters are wired in parallel check system continuity

iv. Fire inter-layer heaters from VMTF prgram. Verify RC, V heaters, I heaters from data logger plots

(f) Disable Digital QDC (or set to high tresholds)

(g) Balance quench detection circuitry for analog QDC

i. Set dump delay to 0 sec

ii. sawtooth ramps between 50 A and 200 A at 100 A/sec.

iii. Establish thresholds based on observed noise versus anticipated signals.

(h) Balance quench detection circuit for DQDC

(i) Set dump delay to 20 msec and the heater delay to 0msec. Manual trip at 1000 A. **Every single analog QDC platform has to be checked separately. Power supply, dump switch, heater and interlock respond should follow the proper quench logic.** Delay heater firing to 1 sec dump delay = 0 sec. Do another manual trip and check L/R, look at all data logger voltage signals; compare V_{max} to $I * R_{dump}$

2. Quench Heater Protection test

   (a) Set dump resistor delay to 0 ms, no heater delay, no power supply phase off delay

   (b) At 2500A magnet current, determine voltage required to quench heaters with $t_{fn} < 200$ ms

   (c) If MIITS o.k dump delay to 20 ms, delay heater firing to 0 ms

   (d) Check quench logic signal for proper quench timing sequence

3. Strain gauge run

   (a) Dump resistor set to 60 mΩ, 20 ms delay , delay heater to 0 ms, heater value as perr 0.2.3 2.b

   (b) At Ramp rate = 20 A /sec. :
   Measure the inductance of the magnet.Make sure to run "snapshot" script. Take strain gauge runs, one file per current loop, using the sequences of currents below.

i. Run 1: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 7100 A and from 7100 A to 0 A. Disable “fast strain gauge” script.

ii. Run 2: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 8400 A and from 8400 A to 0 A. Disable “fast strain gauge” script.

iii. Run 3: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 9000 A and from 9000 A to 0 A. Disable “fast strain gauge” script. 9000 A

iv. Run 4: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 9500 A and from 9500 A to 0 A. Disable “fast strain gauge” script. 9500 A

v. Run 5: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10000 A and from 10000 A to 0 A. Disable “fast strain gauge” script. 10000 A

vi. Run 4: Enable “fast strain gauge” script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10500 A and from 10500 A to 0 A. Disable “fast strain gauge” script. Note: After Run 1, expect quench during strain gage run

4. Quench plateau.

   Before each quench measure the inductance of the magnet. Make sure that the inductance remain unchanged. With ramp rate = 20 A/sec, train the magnet. Do not do more than 5 quenches. The predicted short sample limit currents (inner coil) is 10340 A. Make sure to run “fast strain gauge” and “snap-shot” scripts.

5. RAMP RATE dependence studies.

   Ramp to quench at 300 a/s, 150 a/s,

A.2.4 At 1.9K Operation

1. Cold Electrical tests prior to current excitation Repeat section 0.2.3 1.c,d,e

2. Quench Heater Protection Test Repeat Section 0.2.3 2.a,b,c,d with 3000A applied current.

3. Strain gauge run
   (a) Repeat Section 0.2.2 4.a
   (b) At Ramp rate = 20 A /sec. :
   Measure the inductance of the magnet.Make sure to run "snap-shot" script. Take strain gauge runs, one file per current loop, using the sequences of currents below.
      i. Run 1: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 10000 A and from 10000 A to 0 A. Disable "fast strain gauge" script.
      ii. Run 2: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 11000 A and from 11000 A to 0 A. Disable "fast strain gauge" script.
      iii. Run 3: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 11800 A and from 11800 A to 0 A. Disable "fast strain gauge" script.
      iv. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 12700 A and from 12700 A to 0 A. Disable "fast strain gauge" script.
      v. Run 5: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 13400 A and from 13400 A to 0 A. Disable "fast strain gauge" script.
      vi. Run 4: Enable "fast strain gauge" script. Ramp the magnet with 20 A/sec ramp rate from 0 A to 14200 A and from 14200 A to 0 A. Disable "fast strain gauge" script. Note: After Run 1, expect quench during strain gage run

4. Quench plateau.

   With ramp rate = 20 A/sec, train the magnet until 4 plateau quenches have occurred. Do not do more than 15 quenches (only if magnet shows interesting behavior). The predicted short sample limit currents (inner coil) is 13900 A. Make sure to run "fast strain gauge" and "snap-shot" scripts.

5. RAMP RATE dependence studies.

Ramp to quench at 300 A/sec, 200 A/sec, 150 A/sec, 100 A/sec, 75 A/sec, 50 A/sec

6. Magnetic measurements

   The default ramp rate is 20 A/sec.

   The nominal data set is 25 rotations of the coil.

   All measurement sequences should begin with a "cleansing" quench at ~ 10000A. A cleansing quench is done by firing the magnet heaters with magnet current high enough to produce a small remnant field.

   (a) Remove the quench antenna and install the measurement rig.
   (b) Set the heater delay to 0 sec, dump delay to 20 msec, and dump resistance to 60 mΩ.
   (c) Determine the minimum magnet current for a cleansing quench: check the effect of a cleansing quench at 10000 A by checking the remnant magnetic field. If the remnant field is substantial increase the current and quench the magnet again. Repeat this proceedure until the minimum current is found. Use this value of the current for all cleasing quenches needed for this test plan.
   (d) Remove pre-amplifiers used for warm measurement if this has not already been done.
   (e) Set magnet measurement coordinate system as per TD-98-xxx. File the completed note with this run plan.
   (f) Z scans: take measurements at 8 different z locations along the length of the cold mass: 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.0 m.
       i. Make Z scan at 2000 A
          A. Estimate magnet center and compare to the predicted value.
       ii. Make Z scan at 6000 A
       iii. Make Z scan at $I_{quench} - 500$ A
   (g) End scans (lead end): measure between 1.4 and 2.5 m in 10 cm steps (± 50 cm from the nominal magnet end at 2.0 m.)

i. Make end scan at 2000 A

ii. Make end scan at $I_{quench} - 500$ A

(h) Make a "hysteresis loop" measurement at magnet center (z =0.819 m): make three consecutive loops from I_{min} to $I_{quench} - 500$ A with continuous measurement. We define I_{min} as a current near to the injection current; I_{quench} is the quench plateau current reached following training .

(i) Make a standardization cycle measurement: ramp to flattop current, $I_{plateau} = I_{quench} - 500$ A, dwell at $I_{plateau}$ for t_{dwell} ramp down to 50 A, dwell for 2 sec, ramp to 800 A; wait $t_{injection}$, then ramp to $I_{quench} - 500$ A at 20 A/sec.

Default parameters are $I_{plateau} = I_{quench} - 500$ A; $t_{dwell} = 30$ min.; $t_{injection} = 30$ min.

(j) Analyze the data from the standardization cycle measurement. If "dynamic effects" are seen in the data, the following measurements will be made. (Wait to perform these measurements UNTIL the data have been analyzed, if necessary, continuing the measurement program with item (k).)

i. Repeat the standardization cycle with different $I_{plateau}$. The other parameters remain the same.

ii. Repeat the standardization cycle with yet a different $I_{plateau}$. The other parameters remain the same.

iii. Pick an $I_{plateau}$ from the above list and repeat the standardization cycle with a different t_{dwell}.

iv. Pick an $I_{plateau}$ from the above list and repeat the standardization cycle with a different $t_{injection}$.

(k) DC loop ("stairstep" loop): Take continuous measurements during the loop. Stop for 2 min. at each of the following currents: 0, 1000, 2000, 3000, 4000, 5000, 6000, ... $I_{quench} - 500$ A on both the up ramp and down ramp.

(l) Repeat the hysteresis loop of (g) with different ramp rates: 10 A/sec, 40 A/sec, 80 A/sec.

(m) Repeat the hysteresis loop of (g) at 2 different z positions (z =1.056, 0.706 m[1])

(n) Remove the measurement rig and install the quench antenna

7. Heater studies at 1.9K

   (a) Set dump resistor delay to 1 s, no heater delay, no power supply phase off delay or delay it within MIITs limit (15 MIITs)

   (b) Outer Heater study

      i. At $I/I_c = 0.2$ magnet current determine Vmin for quench. Fire heaters at additional voltage value 400V.
      DO NOT EXCEDE MAXIMUM HFU VOLTAGE

      ii. $I/I_c = 0.4$ determine Vmin for quench. Fire heaters at additional voltage value 400V.
      DO NOT EXCEDE MAXIMUM HFU VOLTAGE

      iii. $I/I_c = 0.7$ determine Vmin for quench. Fire heaters at additional voltage value 400V.
      DO NOT EXCEDE MAXIMUM HFU VOLTAGE

      iv. $I/I_c = 0.9$ determine Vmin for quench. Fire heaters at additional voltage value 400V.
      DO NOT EXCEDE MAXIMUM HFU VOLTAGE

   (c) Interlayer heater study. Repeat outer heater study.

   (d) Spot heater study. Make sure to be within the MIITS limit.

      i. Use the interlayer heater for protection. Set SHFU to 400V. Use Inner pole (Q4) spot heater to initiate quench. Set the spot heaater HFU to 25V. Fire the spot heater at following magnet current values: 5000A, 7000A, 9000A, 10000A, 12000A. Check the 14AA - 14A voltage segment voltage rise to check the that the gain was set properly.

---

[1]This was chosen to match the measurements of HGQ002. We were limited to 0.706 m by the stroke of the measuring apparatus. One could chose to move to a smaller z for HGQ003. Note that for HGQ002, we also made measurements at magnet center +0.25, 0.50, 0.75, 1.00 m (without cleansing quench)in an attempt to isolate the location of the magnetic field disturbance seen in the sextupole. We will want to do this again if the same features are seen.

ii. Use the interlayer heater for protection. Set SHFU to 400V. Use Inner midplane (Q4) spot heater to initiate quench. Set the spot heaater HFU to 25V. Fire the spot heater at following magnet current values: 3000A, 5000A, 7000A.

iii. Use the interlayer heater for protection. Set SHFU to 400V. Use outer midplane spot heater to initiate quench. Set the spot heaater HFU to 25V. Fire the spot heater at following magnet current values: 3000A, 5000A, 7000A.

iv. Use the outer heater for protection. Set SHFU to 400V. Use Inner pole (Q4) spot heater to initiate quench. Set the spot heaater HFU to 25V. Fire the spot heater at following magnet current values: 7000A, 10000A.

8. Quench Current vs. temperature

   Ramp magnet to quench at 20 a/s at the following temperatures

   1.8K, 2.1K, 2.7K, 3.2K, 3.7K, 4.2K

   should not be exact value (± 0.2 K)

9. RRR measurement

   Perform 4 wire measurement using DMM. The applied current should be 5amps and applied only during data taking. Take reading in every couple hours, however make sure that there is a measurement taken when the magnet temperature is between 15 - 20 K.